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Optimization of laser cutting processes using design of experiments

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Abstract

We report on the optimization of laser cutting of thin Al_2O_3 ceramic layers using a design of experiment (DOE) approach. DOE allows to separate the most important influencing factors on the targeted cutting process, to clarify their interaction, to reduce the overall amount of parameter sets that need to be examined and to identify the optimized parameter regions, respectively. Using both, a continuous wave 500 W fiber laser and a 200 W CO_2 laser, we have optimized and compared the cutting of 250 μm thin Al_2O_3 ceramic substrate layers applying a commercial DOE software. Our results demonstrate the potential of DOE to optimize laser material processes.

Keywords: Laser based cutting, process optimization

1. Introduction

Laser cutting for shaping and separating workpieces into parts of desired geometry is one of the most widespread tasks of laser material processing. For certain well defined applications, e.g. cutting metal sheet using CO_2-lasers, suppliers of laser cutting machines provide a comprehensive database for process parameters. However, in general new customized cutting processes have to be individually optimized with respect to the targeted geometry and the material to be cut while taking into account the equipment to be used. Since laser cutting processes are often governed by a multitude of parameters, some of which interacting with each other, the optimization of a process is determined by a high degree of complexity. As a consequence, the optimization of an industrial laser process might be a time consuming and cost intensive task, particularly in case simplified methods such as the one-factor at a time approach are applied. In addition, possible interactions of different factors might remain partly unconsidered if such intuitive approaches are chosen.

In this paper, we present an optimization study of laser cutting thin Al_2O_3 ceramic layers using a design of experiment approach (DOE). DOE allows to separate the most important influencing factors on the targeted cutting process, to clarify their interaction, to reduce the overall amount of parameter sets that need to be experimentally examined and to identify the optimized parameter regions, respectively. Within the DOE approach, initially a target value or set of target values has to be defined for specific parameters, referred to as the response. To become acquainted

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with a process in general, DOE uses a screening design to analyze the effect of several influencing variables on the response and to separate the main influencing parameters from those having minor impact on it. A further step within the DOE approach is the response surface methodology, which investigates the local and global optima of the process and which identifies relevant interactions between the influencing variables.

A continuous wave 500 W fiber laser (IPG Photonics) and a 200 W CO_2 laser (Synrad) were used to carry out the experiments in this study. Both laser systems are equipped with two identical portal assemblies with linear stages (Aerotech) and a fine cutting head (Precitec) with a focal length of 50 mm. As an assisted gas nitrogen was applied coaxial to the laser beam. The fiber laser is characterized by a M^2 of 1.01, a raw beam diameter of 7.25 mm and a focus diameter of 10 μm, respectively. The CO_2 laser has a M^2 of 1.17, a raw beam diameter of 10.8 mm and a focus diameter of 74 μm, respectively.

The target parameter and value in our study (i.e. the response) is the burr at the kerf that should be eliminated. We have used an optical stereo microscope (Motic) to determine the height of the burr, the results of which were controlled by a confocal microscope (FRT). Design of experiments were performed using the software package JMP® (SAS International).

2. Screening Design

To get acquainted with the process and to circumvent a suitable parameter region a screening design is performed using the fiber laser. In addition, the screening design identifies whether a factor has a significant influence on the response or not. To evaluate the quality of the process, the burr on the edge of the kerf was measured. The varying parameters have been laser power, cutting speed, distance from the nozzle to the surface, assist gas pressure, position of the focus and diameter of the nozzle, respectively. A generally adopted approach in design of experiments is to use a fractional factorial design instead of a full factorial design. Opposite to the later, a fractional factorial design does not account for higher order interactions, as, e.g., between three influencing variables. We used twelve runs and four center points to examine the response. The measured burr when cutting with the fiber laser has been analyzed using JMP®. In figure 1 the measured burr is plotted over the predicted burr, as being calculated by linear regression. The ideal fit is the 45 degree line and the dotted ones are 95% confidence interval. The horizontal line in the centre of the graph is the mean value of the burr determined from the processed samples. The measured points are closer to the ideal fit than to the mean value. The p-value (i.e. probability value) is less than 0.0001 and considers the evidence that at least one of the parameters has a significant influence on the response. In order to assess the validity of the developed model the R^2 value of 0.84, defined as $\frac{Sum\ of\ Squares_{model}}{Sum\ of\ Squares_{total}}$ shows that the data is well reflected in the model. This means that 86% of the variation in the response could be explained by the influencing factors.

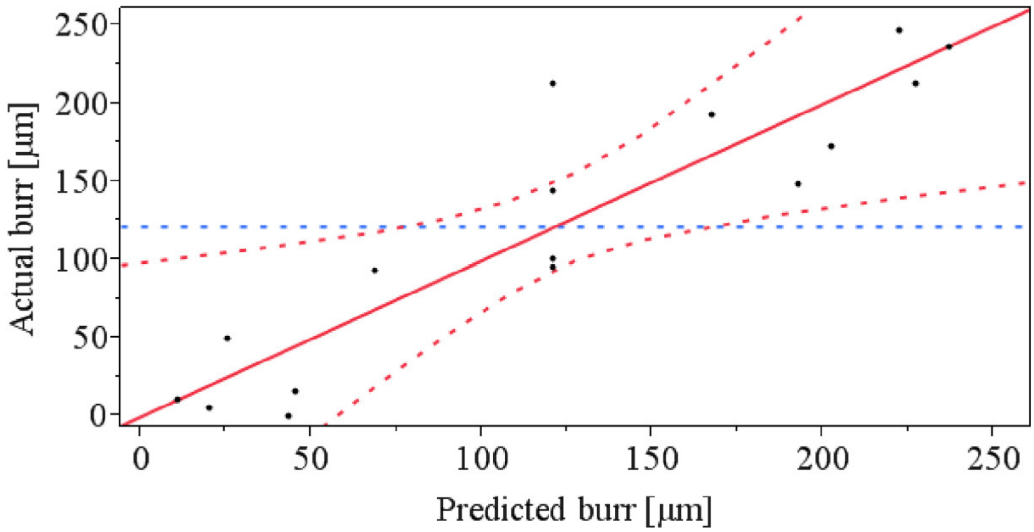

Fig. 1. Actual burr as measured by an optical microscope versus predicted burr (by JMP). Solid line: ideal fit; dotted line: 95% confidence interval; horizontal line: mean value of burr

Analyzing the results of the screening design reveals that using a nozzle with a diameter of less than 0.8 mm will not provide appropriate results. Therefore, throughout this study we used a nozzle with a diameter of 0.8mm. Furthermore, the gas pressure must exceed at least 12 bar and the laser power should be larger than 200 W to avoid burr. If the position of the focus is set on top of the material, its value is defined as zero. Increasing values correspond to a rise over the surface and decreasing values refers to moving the focus into the material. Rising the position of the focus causes a larger spot size and consequently a larger groove. Therefore, the melted material flows out more easily and the probability of burr formation is smaller. Table 1a shows the examined parameter region of the screening design and 1b the optimized region according the conducted design.

Table1. Parameter region

laser power	30 - 80 %
velocity	50 - 150 mm /s
distance of the nozzle	0.1 - 0.8 mm
pressure of gas	6 - 14 bar
position of the focus	0 - 0.5 mm

(a) Parameter region in screening design

laser power	40 - 80 %
velocity	50 - 150 mm /s
distance of the nozzle	0.3 - 0.6 mm
pressure of gas	12 - 20 bar
position of the focus	0.25 - 0.4 mm

(b) Parameter region in following experiments

Figure 2 shows the formation of burr as a function of laser power, velocity, gas pressure, distance of the nozzle and position of focus, respectively. The varying gradient of the dependencies reveals different significance of these parameters on the response (i.e. the formation of burr). However, as all five parameters have an impact on the response they will be further taken into account in the following response surface design.

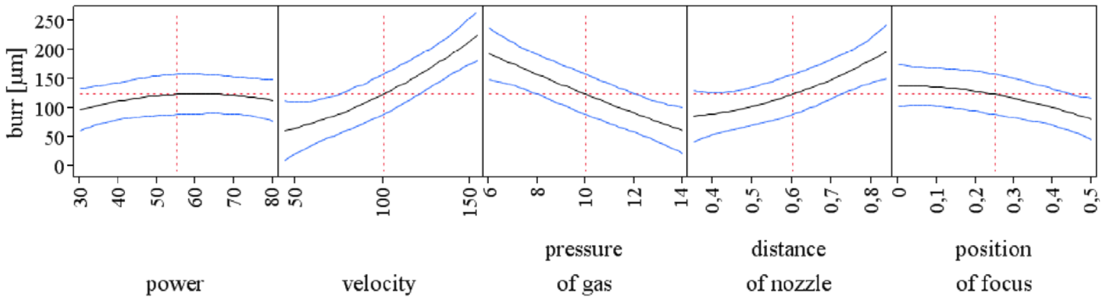

Fig. 2. Influence on response. Burr over different parameters (black line). Blue line: confidence intervals. Larger gradient corresponds to larger influence.

3. Response Surface Design

Based on the results of the screening design, additional parameter settings within the derived parameter region were evaluated and the DOE has been extended to a response surface design. Seven runs were added and one replication of all settings, which sums up a whole number of runs of 46. Figure 3 depicts the five parameters under study in an interaction plot, in which evidence of interacting parameters is adduced by nonparallel lines. The larger the difference between the two gradients of the respective parameters, the stronger the interaction is. Here, the strongest interaction can be found between the position of the focus and distance of the nozzle, whereas the smallest interaction is observed between laser power and position of the focus. Figure 3 clearly reveals the complexity and therefore the challenge in finding an optimum parameter set for the cutting process as several parameters are correlated with each other.

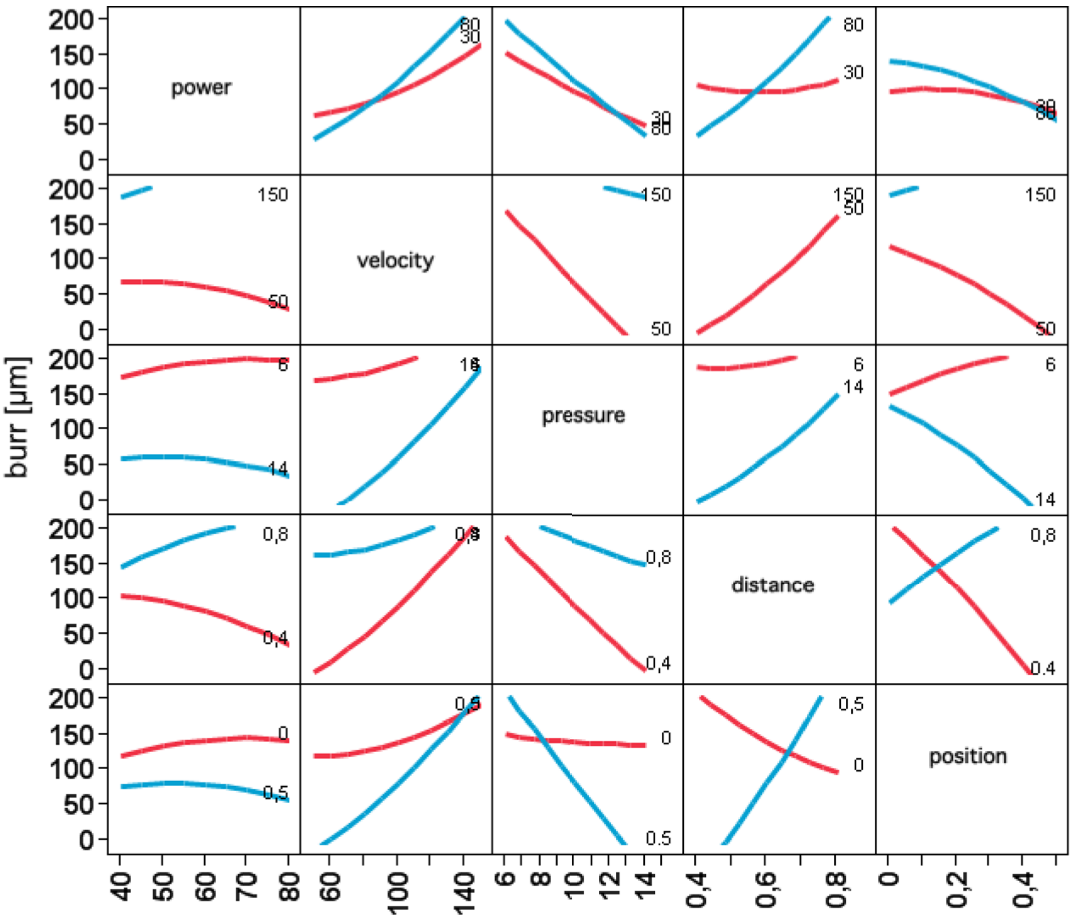

Fig. 3. Interaction plot. Evidence of interaction shown as nonparallel lines.

By using response contour plots, the influences and interactions of parameters have been analyzed to identify the optimum parameter set. In the following figures, selected parameters are illustrated in a contour profiler, which combines response contours for two factors. Figure 4 shows a contour surface of the response (i.e. the burr) versus laser power and velocity, while keeping all other parameters fixed at 12 bar gas pressure, 0.5 mm distance of the nozzle and the position of focus at 0.25 mm, respectively. The grid on the bottom plane of this graph is a guide to the eye and corresponds to a vanishing burr. The intercept between the contour surface and the bottom plane of this graph defines a contour line, which is in case of the laser power depicted in figure 5. A comparison of these contour lines shows that the laser power has a lower influence on burr formation as compared to velocity. However, increasing one of these two parameters necessitates the increase of the other in order to avoid burr.

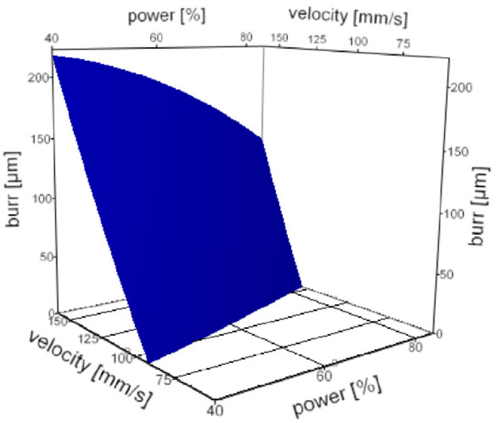

Fig. 4. Contour surface for burr response by power and velocity.

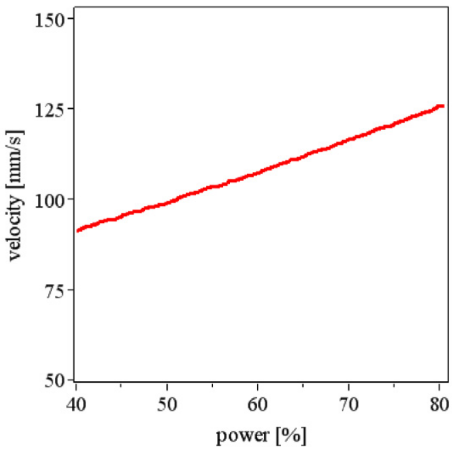

Fig. 5. Contour line from cut of grid and surface.

In figures figure 6 and 7 the contour surface of burr response versus gas pressure and velocity is given. It can be clearly seen that increasing the velocity, i.e. to accelerate the process, demands a higher gas pressure to blow out the molten material.

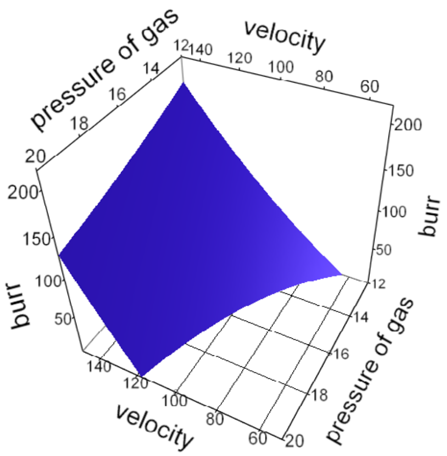

Fig. 6. Contour surface for burr response by pressure and velocity.

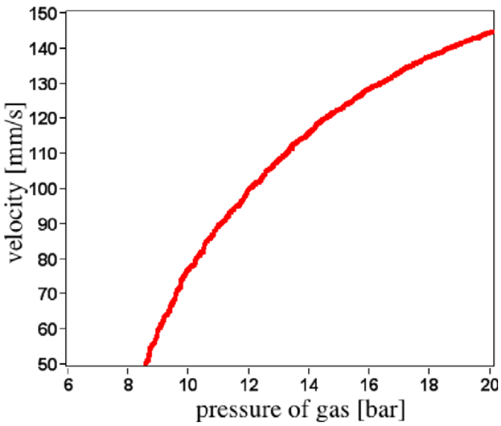

Fig. 7. Contour line from cut of grid and surface.

In the range of small distances from the surface (up to 0.4 mm) the position of the focus is insignificant, but if a larger distance is desired the position of focus has to be increased, accordingly.

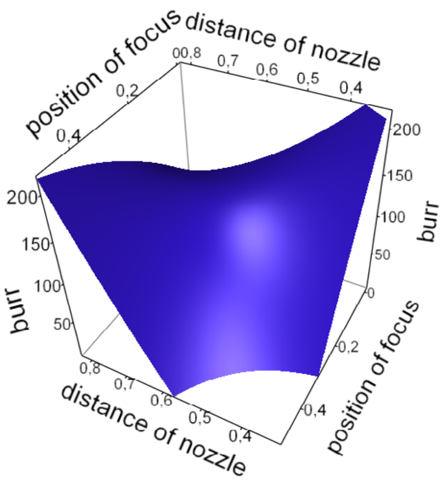

Fig. 8. Contour surface for burr response by distance and position of focus.

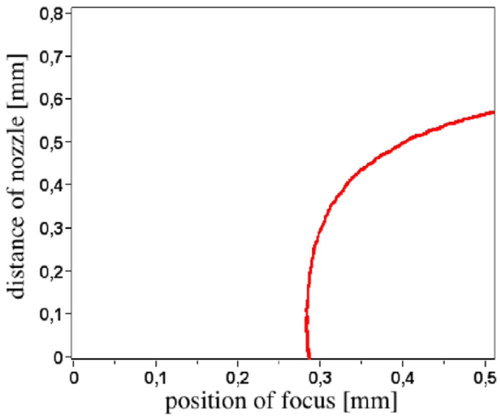

Fig. 9. Contour line from cut of grid and surface.

In summary, the prediction profiler of JMP® suggests a parameter setting and predicts the burr formation, as shown in figure 10. Using the following settings the kerf is free of burr: power of 50 % of its maximum value (i.e. 250 W), velocity of 100 $\frac{mm}{s}$, assist gas pressure of 12 bar, a distance from the nozzle to the surface of 0.3 mm and a focus position of 0.3 mm above the surface.

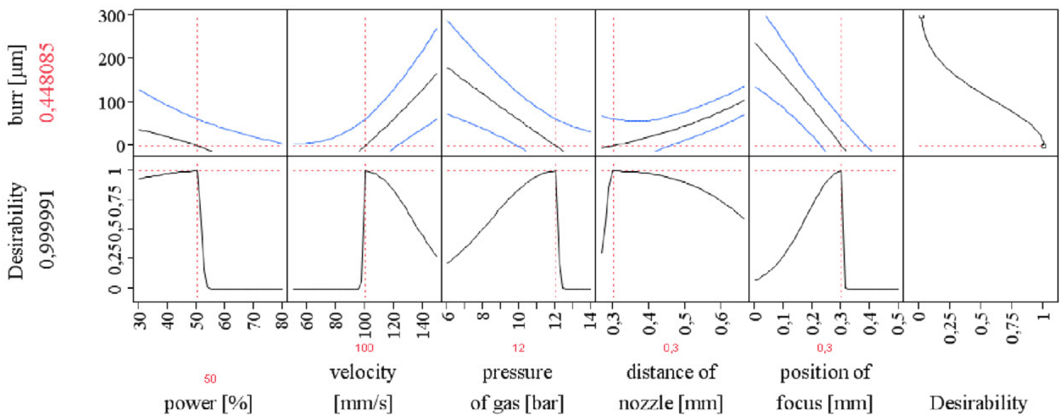

Fig. 10. Suggested parameter setting with predicted value of burr (red value).

This result of the calculation in JMP® has been proved in practice. Figure 11 compares the cutting edge as being cut with the optimum parameter set according DOE (bottom) and another arbitrarily chosen parameter set.

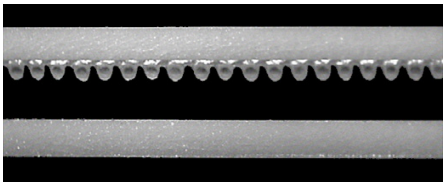

Fig. 11. Upper kerf: performed with arbitrarily chosen parameter set; lower kerf: performed with the optimum parameter set (by JMP®).

4. CO2 - Laser

The same DOE approach as described for the fiber laser has been applied to optimize the laser cutting process of thin Al_2O_3 ceramic layers when using a 200 W CO_2 laser. For the model of the screening design JMP® has calculated an R^2 value of 0.93, which shows that the data of the experiment are well fitted in the model. The small p-value (<0.0001) reflects that at least one factor has a significant influence on burr formation. Figure 12 illustrates the formation of burr as a function of laser power, velocity, distance of the nozzle, position of the focus and gas pressure, respectively. Based on this screening design we conclude that the most significant factors are velocity and gas pressure. Nonetheless, all parameters are taken into account to create the response surface design when using the CO_2 laser to create a full understanding of the process.

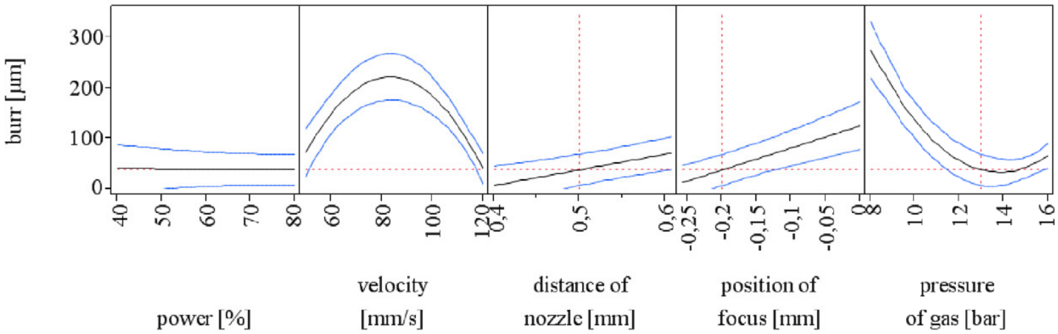

Fig. 12. Influence on response. Burr over different parameters. Blue line: confidence intervals. Larger gradient corresponds to larger influence.

Qualitatively, the results of the response surface design are analyzed similarly to those we got when using the fiber laser. However, here we focus on the analysis of the interaction between velocity and gas pressure as they exhibit the strongest correlation (figure 13 and 14). To obtain a faster process higher pressure of gas is needed.

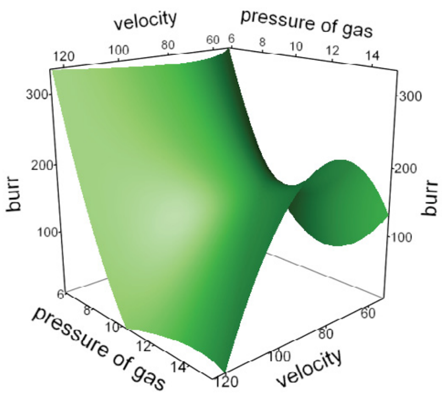

Fig. 13. Contour surface for burr response by velocity and pressure of gas.

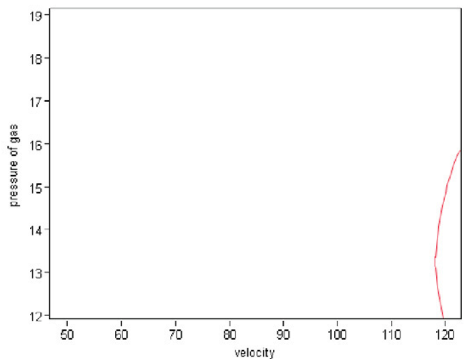

Fig. 14. Contour line from cut of grid and surface.

Based on this analysis, JMP® provides a parameter set that ensures burr free cutting of the Al_2O_3 substrate: laser power 180 W, velocity at 120 $\frac{mm}{s}$, gas pressure 12 bar, distance of the nozzle at 0.4 mm and the position of the focus at the bottom of the material (i.e. -0.25 mm). Table 2 represents the two identified parameter sets of the different laser systems.

Parameter	**Fiber laser**	**CO_2 laser**
laser power	250 W	180 W
velocity	100 mm /s	120 mm/s
distance of the nozzle	0.3 mm	0.4 mm
pressure of gas	12 bar	12 bar
position of the focus	0.3 mm	-0.25 mm

Table 2: Comparison of the optimized parameters of the two laser systems

5. Summary

In summary, we have demonstrated the potential of a design of experiment (DOE) approach in optimizing laser material processes. Specifically, we have optimized the laser cutting of thin Al_2O_3 ceramic layers in a comparative study using both fiber and CO_2 lasers. In case of the fiber laser, the developed design encompassed only 46 individual experiments taking into account five individual influencing factors. Based on this method the entire process including an analysis of the interaction between different parameters was studied. As compared to more intuitive approaches as one factor at a time this highlights the possibility to significantly reduce the overall efforts needed to optimize laser processes. In addition, DOE identifies all interactions between the parameters under study. For both laser systems DOE delivers the optimized parameter sets for the cutting process which are defined by a vanishing burr. The different parameter sets for the two laser systems can be explained by the specific beam properties of the respective lasers.

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